SMART SHOE: PORTABLE GAIT MONITORING SYSTEM UTILIZING INERTIAL MEASUREMENT UNIT (IMU)

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ABSTRACT

Gait analysis is a principal element to the field of biomechanics, with its application in sport, rehabilitation and correction of biomechanical dysfunctions to upgrade the quality of life. Complex gait analysis system, while important for human rehabilitation, often relies on expensive and high technology equipment like 3D optical monitoring device and force plate. This study presents the development of a portable, affordable gait monitoring system using MPU6050 Inertial Measurement Unit (IMU) and ESP32 microcontroller. The system is integrated into a Smart Shoe, utilising a gyroscope within the MPU6050 sensor to capture ankle angle data. Healthy participants were selected and ankle angle data were recorded in real-time during walking trials. The ankle angle data were wirelessly transmitted to a smartphone through Blynk application. Results demonstrate that the Smart Shoe system is capable of detecting gait phases based on the collected ankle angle data which produce consistent gait pattern during normal walking condition. Despite its affordable price, it can produce result that is comparable with other wearable sensor device, offering a solution for broader application in rehabilitation and disease detection.

Keywords: *IMU, Gait analysis, Monitoring system.*

1.0 INTRODUCTION

Road accidents in Malaysia are increasing every year, which include pedestrians, motorcycles, cars, and other vehicles. According to the Malaysian Ministry of Transport, the 2019 statistics showed that there were 567,516 road accidents in Malaysia [1]. For individuals facing lower limb injuries during road accidents, rehabilitation is necessary to recover their ability to walk as a normal person [2]. This involves gait training, which is designed to exercise the body's movement pattern and avoid re-injury during ambulation [3]. To efficiently evaluate the outcomes of rehabilitation, a deep understanding of lower limb movement and the biomechanics of human locomotion is essential for therapies [4].

In the book Dynamics of Human Gait by C.L. Vaughan (1999), the lower limb movements are categorized into stance and swing periods. This period consists of eight distinct phases, as illustrated in Figure 1. Vaughan explains that during the stance phase, the foot remains in contact with the ground, whereas in the swing phase, the foot is off the ground, and the leg swings forward in preparation for the next foot strike. The eight gait

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phases identified by Vaughan are termed heel strike, foot-flat, midstance, heel-off, toe-off, acceleration, midswing, and deceleration. The terminology of gait phases used by Vaughan is quite different from that used by J. Perry in their book Gait Analysis. Despite the different terminologies, the angles and limb positions during these phases are consistent with those described by J. Perry. Additionally, Vaughan divides the overall stance phase into three sub-phases: the first double support phase (heel strike and foot flat), the single limb stance phase (foot flat to heel off), and the second double support phase (heel off to toe off) [5].

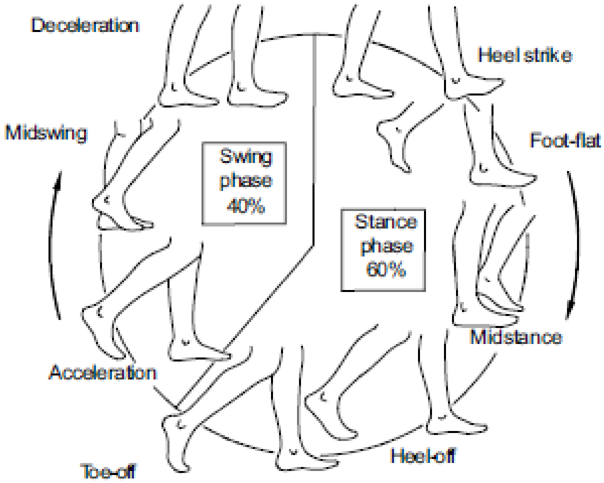

Figure 1: Eight different phases in gait cycle [5]

Although a normal human gait is typically divided into eight gait phases, there are situations where this phase may be combined or simplified. This approach helps researchers to reduce errors in analysis. For example, in the study conducted by B. Abinaya (2012), the air pressure sensor used in their research unable to detect any ground contact force(GCF) between the swing phases caused three phases within the swing phase were combine into one. As a result, the total gait phases observed in their study were reduced to six gait intervals [6]. However, eight gait phases are utilized to analyze human motion using a Smart Shoe.

Gait analysis is a principal element to the field of biomechanics, with its application in sport, rehabilitation and correction of biomechanical dysfunction to upgrade the quality of life [7]. Moden gait analysis system, while important for human rehabilitation, often relies on expensive equipment such as motion capture [8][3] and 3D monitoring system [24]. Moreover, this complex technology requires a permanent space and is limited only to a few clinics or research centers [9]. Furthermore, this equipment requires an advanced training for preparing the laboratories such as placing markers and handling anthropometric measurement [10]. This limitation prevents their accessibility and widespread application particularly in resource-constrained setting.

To focus on this challenge, this study proposes the development of a portable and affordable gait monitoring system using MPU6050 inertial measurement unit (IMU). IMU, consisting of accelerometer, gyroscopes and magnetometers, offers a simple and affordable solution for capturing movement data [11]. By manipulating the gyroscopes within the IMU to measure ankle angle, this system aims to analyse gait phase detection without sacrificing accuracy [12].

The proposed system is integrated into Smart Shoe which provides real-time data collection and wireless transmission to a smartphone application for monitoring [13]. This approach not only reduces the cost and complexity of existing system but also enhances its portability and user-friendliness. By focusing on ankle angle data, the system organises the analysis process while still providing valuable information into gat pattern [14].

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The development of this portable and affordable solution has the potential to innovate gait monitoring in various applications including early disease detection [15], rehabilitation progress tracking [16], and sport performance enhancement [17]. Finally, this research contributes to the advancement of accessible and affordable gait analysis technology with the potential to improve healthcare outcomes and upgrade the quality of life for individuals across the various populations.

2.0 METHODOLOGY

In this study, several steps are involved which starts from the research of hardware and software to be used for developing a portable gait monitoring system. The main component of a gait monitoring system is the ESP32 WROOM 32 microcontroller, which is selected based on its size, versatility, multi-function and compatibility with various sensors. Central to data acquisition is the MPU6050, an inertial measurement unit (IMU) equipped with a 3-axis accelerometer and gyroscope. This IMU was chosen for its compact form factor, affordability and adequate accuracy in capturing ankle angle data, which is a critical parameter for gait analysis.

To increase user experience and facilitate real-time analysis, the Blynk smartphone application was utilized. This application allows for satisfactory visualization and interpretation of gait parameters transmitted wirelessly from the Smart Shoe. The Arduino IDE serves as the programming environment for the microcontroller, while the Blynk library enables smooth communication between the hardware and software components.

After successfully establishing hardware connection, coding and equipment calibration, the repeated testing was conducted to ensure the Smart Shoe is able to read the gait cycle data from a healthy human subject and transmitted to smartphone application. Data from ankle angle movement in x-axis and total time to complete gait cycle were collected from MPU6050 during testing. The overall system framework of the portable Smart Shoe is illustrated in Figure 2. The system utilises an ESP32 microcontroller to wirelessly collect ankle angle movement data through the Blynk application.

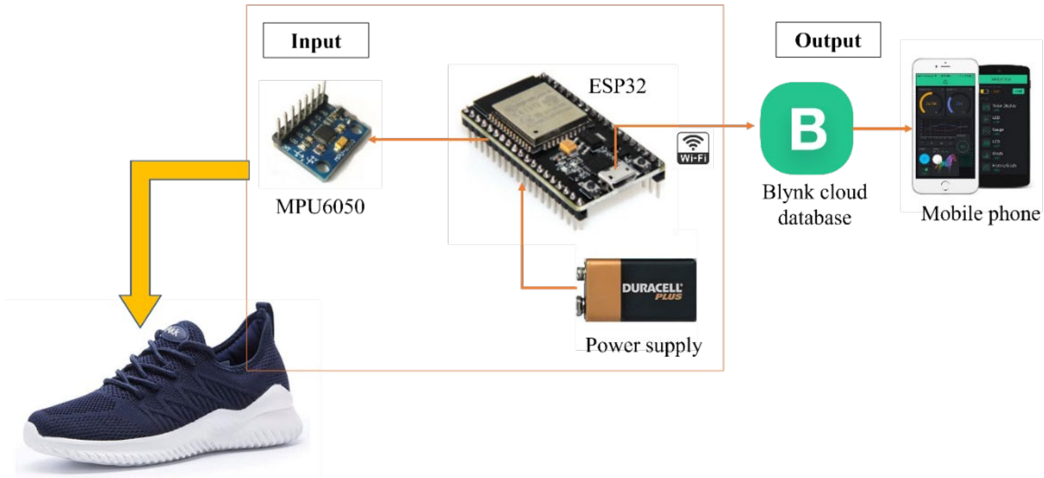

Figure 2: Overall system of portable Smart Shoe

Data collection then extracted relevant gait parameters and presented them in both data and graphical formats for extensive evaluation and interpretation. To ensure the functioning of this gait monitoring device, a previous result from past research and articles would be used as reference to validate the result obtained from Smart Shoe. The result is expected to show a normal curve of ankle angle differentiation during a walking sequence.

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2.1 Inertial Measurement Unit Position

A system that integrated inertial measurement unit into gait analysis system typically operates by attaching the IMU directly to specific body parts of the subject such as shanks or ankle. This is because, an IMU which integrated with an accelerometer and gyroscope can detect acceleration and changes in ankle angle during walking activity. However, the position and the orientation of the equipment must be carefully considered to ensure precise data collection because the accelerometer and gyroscope both have their own X, Y and Z axis. Research study by T. Tan (2019) found that the error in the position of IMU was one of the largest contributors to the error in data obtained, compared to other factors such as manufacturing variation and environmental conditions [18]. Tan stated that this happens because the estimation model used in the gait analysis system learns to relate the input and output based on the training data. As shown in Figure 3, the research results indicate that the error in IMU orientation can result to data accuracy of 82%, whereas data with no orientation can achieve almost 95% accuracy. Additionally, the accelerometer within the IMU can be affected by both orientation and position placement errors, while the gyroscope is only affected by orientation placement errors [18].

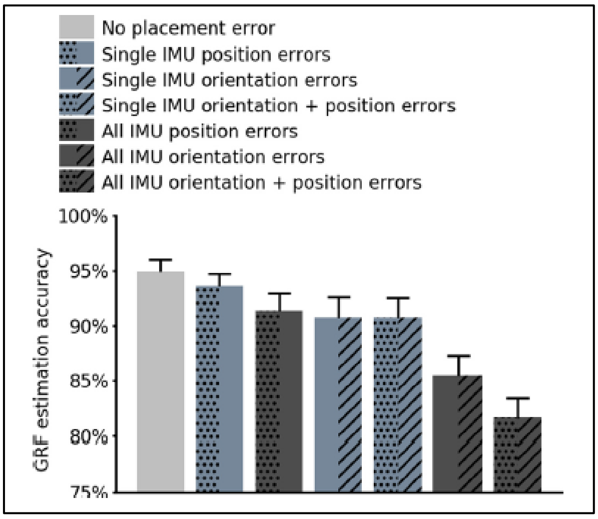

Figure 3: Effects of position and orientation error to IMU accuracy graph [18]

A study by M. Zrenner (2020) investigated the ideal position for shoe-mounted Inertial Measurement Unit (IMU) sensors. The IMU was evaluated in four different positions on the shoe: the insole cavity, lateral position, instep position, and heel position, as illustrated in Figure 4. Raw data from the IMU at these various positions were collected and compared across subjects using Pearson's correlation coefficients [19].

The findings revealed no single sensor position significantly outperformed the others, validating the data obtained from all positions. However, from a data processing perspective, the insole cavity was identified as the optimal position for the IMU. This placement is unobtrusive and ensures secure attachment within the shoe sole, minimizing additional movement of the shoe relative to the actual walking activity, thereby providing the highest quality raw signals [19]. Despite this, for research conducted using the Smart Shoe, the heel position was chosen, considering factors such as sensor installation and maintenance.

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Name	Mounting
Cavity	Cavity cut in the sole of the shoe under the arch
Instep	Mounted with suiting clip to laces of the shoe
Lateral	Mounted with tape laterally under ankle
Heel	Mounted with tape on heel cap

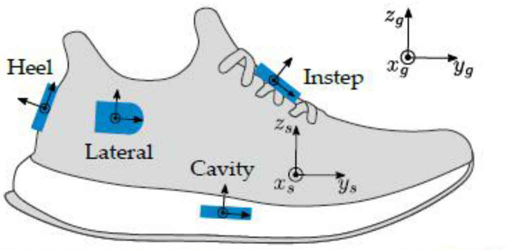

Figure 4: Ideal IMU position on shoe [19]

2.2 Hardware Construction

Figure 5 illustrates the detail circuit diagram connections between the MPU6050 and ESP32, while Figure 6 shows the assembly components into the Smart Shoe. The hardware construction process involves connecting the circuit components and integrating them into a sport shoe within a custom-designed box. To minimize discomfort during walking activities, lightweight materials were selected for the box housing MPU6050 sensor and ESP32 microcontroller. 40mm jumper wire is used to ease the electrical connections between these components.

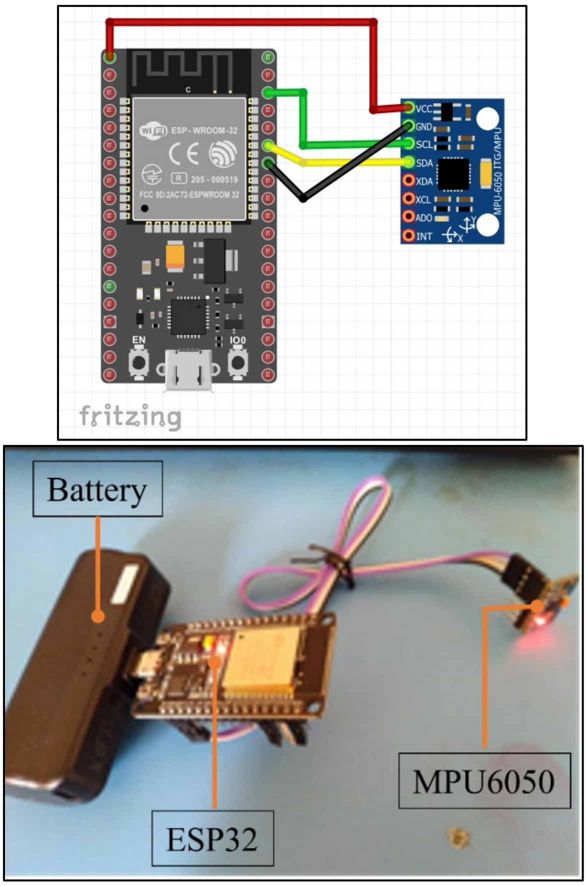

Figure 5: Circuit connection diagram of smart shoe

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Figure 6: Assembly device

2.3 Software Integration

The software integration process involves developing programming code for both the ESP32 microcontroller and the Blynk smartphone application through Arduino IDE platform. The coding was constructed to read the raw data from MPU6050 sensor, converting it into useful ankle angle value, and transmitting the data wirelessly to the smartphone. The Blynk application, in turn, receives this data, processes it for gait analysis, and displays the results in real-time through an intuitive user interface.

To understand the coding easily, a flowchart was developed as shown in Figure 7. The flowchart begins with the Setup Function, which initializes the hardware components (MPU6050 IMU and ESP32 microcontroller) and establishes a connection with the Blynk application. The IMU is then calibrated to ensure accurate readings by calculating the offset of current gyroscope.

The main functionality resides in the Loop Function, which runs continuously. This function reads raw data from the IMU, calculates the ankle angle using sensor fusion algorithms, and sends this data to the Blynk app every 10 milliseconds. The Blynk app receives the data, processes it, and displays the results in real-time.

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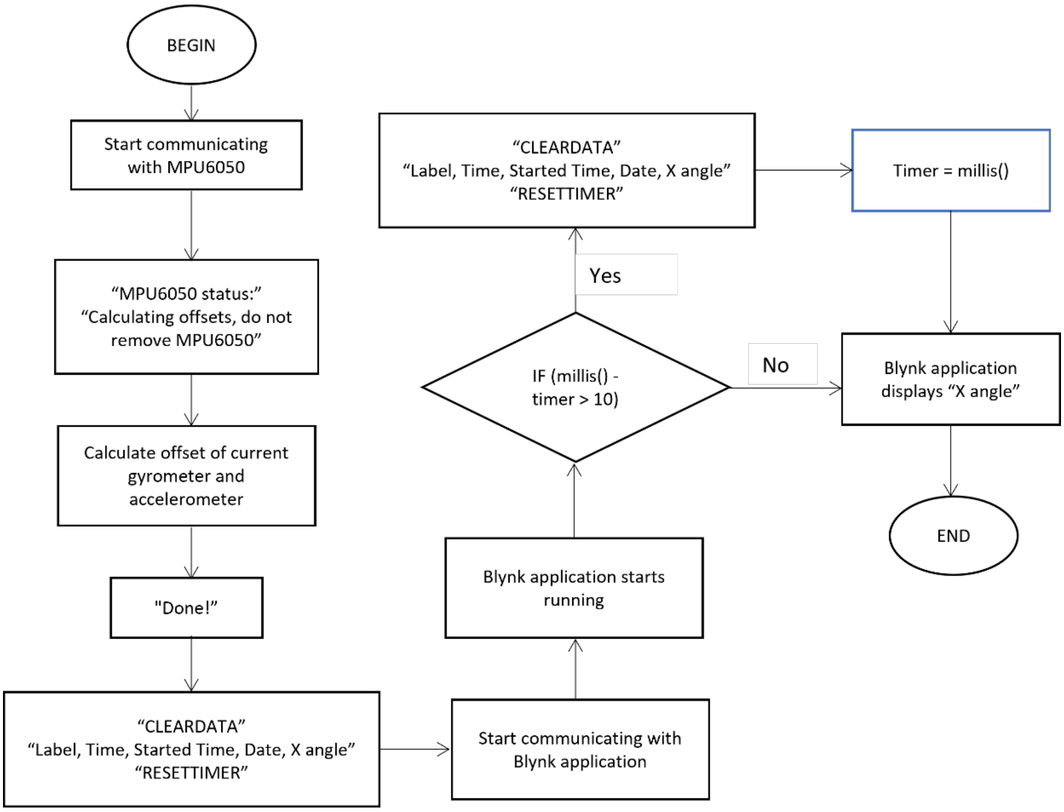

Figure 7: Flow chart of Smart Shoe for collecting dan monitoring ankle angle data

2.4 Experimental Procedure

Figure 8 illustrates the experimental setup for acquiring human ankle angle data during walking conditions. Healthy participants were recruited for this study to assess the performance of Smart Shoe. Before each trial, participants were required to maintain a static standing position for several seconds to facilitate initial system alignment [20]. During each trial, participants were instructed to walk at a self-selected pace along a 10-meter unobstructed linear path. Participants were asked to execute normal gait patterns in a forward direction, returning to the starting point at the conclusion of each trial. This protocol was repeated ten times to ensure data reliability [21].

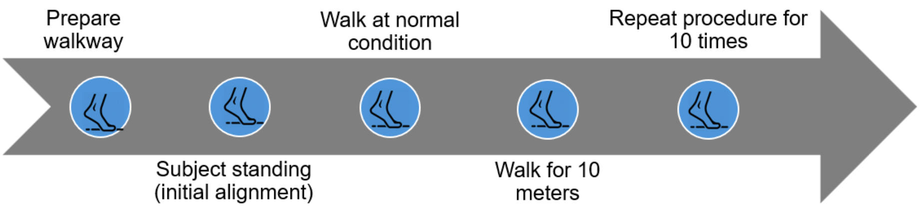

Figure 8: Experimental procedure to evaluate Smart Shoe

3.0 RESULTS AND DISCUSSION

To ensure affordability, the hardware components were procured in limited quantities and at competitive prices. This Smart Shoe can be considered inexpensive, costing only around RM50. Table 1 presents a breakdown of the equipment used in the Smart Shoe, including their individual costs and the quantity required.

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Table 1: Bill of material

Equipment	Quantity	Price (RM)
Inertial measurement unit (MPU6050)	1	9.35
Microcontroller with Wi-Fi module (ESP32)	1	16.89
Jumper wire	4	1.00
Power source (Mini power bank)	1	23.50
	Total	**50.74**

Moreover, its portable nature of this Smart Shoe eliminates the needs for patients to be assessed at specific facilities, thereby reducing limitations in employing this device. To use this device for assessment, it only requires a 5 to 10 metres space with a flat floor to facilitate patient during walking.

3.1 Data Analysis

To assess the credibility and viability of the Smart Shoe, the data collection from Smart Shoe during normal walking condition was analysed. The gait pattern, timing, and ankle angle measurements were compared to those of previous studies to verify the Smart Shoe's ability to accurately detect the gait cycle. Multiple data collection trials were conducted to enhance the accuracy of the results.

Analysis of the ankle angle data revealed that the gait cycle graph could be separated into distinct phases based on the observed patterns. Figure 9 illustrates a sample gait cycle divided into eight phases: initial contact (IC), loading response (LR), mid-stance (MST), terminal stance (TST), pre-swing (PS), initial swing (IS), mid-swing (MSW), and terminal swing (TSW).

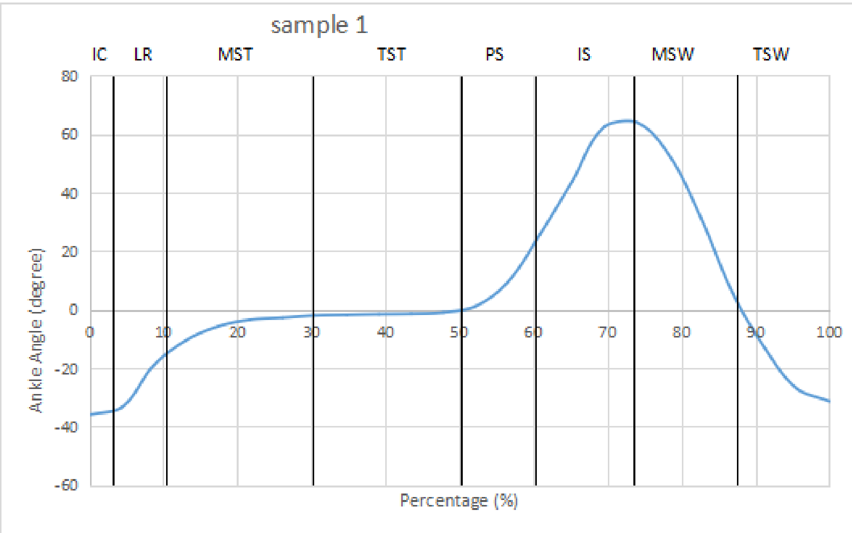

Figure 9: Gait phase division in one complete gait cycle

After successfully conducted 10 sets of experiment, the best gait cycle from each experiment was selected to be analysed and compared with each other. Figure 10 illustrates the minimum, maximum, and average readings across ten gait cycles. Notably, readings began to diverge substantially from each other starting from the pre-swing phase, with several peaks observed in the maximum ankle angle readings. This variability is primarily attributed to differences in timing among subjects, particularly during the swing phase. These timing inconsistencies resulted in some gait cycles experiencing a faster swing phase

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than others. Implementing a treadmill to control walking speed could potentially mitigate this variability.

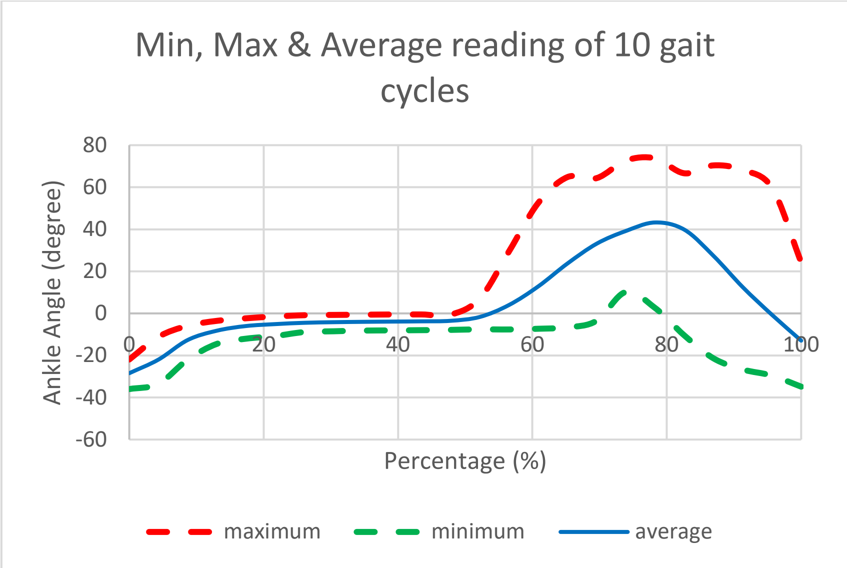

Figure 10: Graph of maximum, minimum and average reading of ankle angle

Table 2 presents the intervals or phases identified within a single gait cycle. A total of eight phases were observed, each contributing a specific percentage to the overall cycle, culminating in a complete 100% gait cycle. These phases were defined based on their ankle angle range, foot position, and percentage of cycle completion. The transition from one phase to the next was seamless, with the final phase leading directly into the initial phase of the subsequent gait cycle. Each phase also exhibited distinct types of flexion, as indicated by the ankle angle. Negative angles signified dorsiflexion (anti-clockwise foot movement), while positive angles indicated plantar flexion (clockwise movement). Angles at or near zero degrees represented a neutral foot state. The percentage completion data in closely aligned with the gait phase percentages reported in Perry's "Gait Analysis" [22].

Table 2: Average gait phase data for 10 gait cycle

Gait Phase	Ankle Angle (º)		Flexion Dorsi (DF) Plantar (PF)	Period (s)	Percentage (%)
	Start	End			
Initial contact	-28.44	-21.96	DF	0.11	0.00
Loading response	-21.96	-11.09	DF	0.15	4.14
Mid stance	-10.02	-4.03	DF to neutral	0.55	10.21
Terminal stance	-4.03	-2.67	Neutral	0.48	32.18
Pre swing	-2.67	21.69	PF	0.30	51.05
Initial swing	21.69	66.02	PF	0.27	62.91
Mid swing	66.02	10.14	PF	0.30	75.36
Terminal swing	10.14	-33.64	DF	0.37	85.63

The mid-stance phase exhibited the longest duration, averaging 0.55 seconds. This extended duration is attributed to the foot traversing the greatest distance during this phase.

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Additionally, the mid-stance phase was unique in demonstrating two distinct flexions: dorsiflexion transitioning to a neutral state. During this phase, the body's weight is supported by a single limb while the other limb is lifted for forward progression. Consequently, a longer duration is necessary to establish limb and trunk stability, ensuring unimpeded advancement.

3.2 A Comparative Assessment of Gait Phase Detection Capabilities

A gait parameter collected from a healthy person that was recorded during single walking experiment is compared with the research by S.J. Morris Bamberg (2004) using "GaitShoe". This comparative assessment is summarized in Table 3. For pitch parameter, the "GaitShoe" wearer gait range is slightly different than Smart Shoe range, with a mean 4.1° beyond for maximum pitch, and a mean 0.8° beyond for minimum pitch. Meanwhile, the stride time of the Smart Shoe wearer is larger by 1.46s. It means, "GaitShoe" wearer is walking faster. The percentage of the stride spent in stance is nearly equivalent, with the Smart Shoe subjects spending only 2.69% less time in stance.

Table 3: Comparison of gait parameters between two devices

Parameter	Smart Shoe Mean(σ)	"GaitShoe" Mean(σ)
Maximum Pitch [°]	66.0	70.1
Minimum Pitch [°]	-28.5	-29.3
Stride Time [s]	2.5	1.07
Percent Stance Time [%]	62.9	65.6

Figure 11 illustrates the pattern obtained from ten consecutive gait cycles of Smart Shoe, while Figure 12 shows the gait cycle pattern recorded by the "GaitShoe" system which utilizes the ADXL202E inertial measurement unit [23]. A comparison of both graphs revealed similar patterns in capturing gait cycles on a single plane. This similarity suggests that the MPU6050, employed in the current Smart Shoe system, is a viable option for detecting gait cycles in healthy individuals.

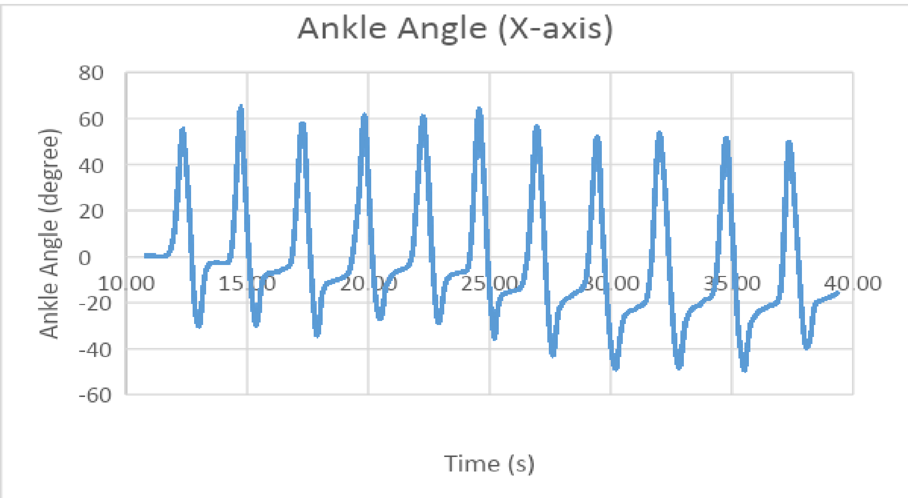

Figure 11: Sample ankle angles recorded in one session from smart shoe

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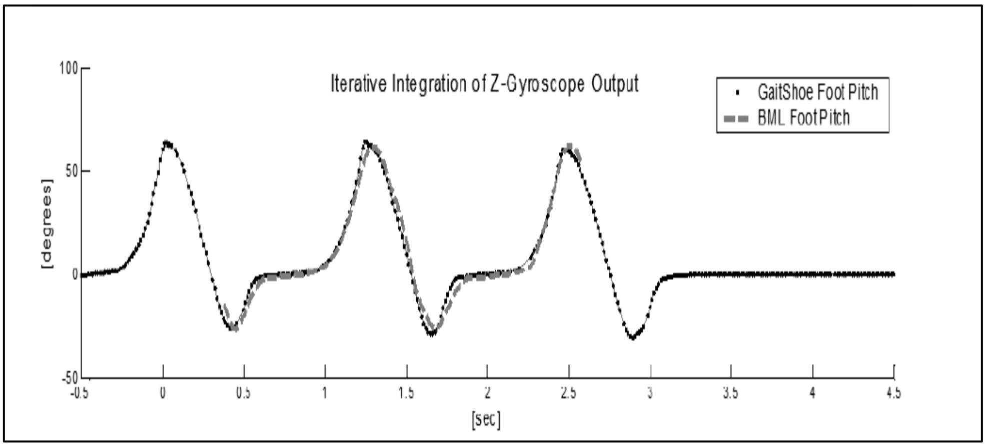

Figure 12: Sample of z-axis gyroscope integration from "GaitShoe"[23]

4.0 CONCLUSION

The research has successfully achieved its objectives by developing an affordable and portable gait monitoring system. This system utilizes low-cost electronic component, including the MPU6050 inertial measurement unit and the ESP32 microcontroller, to transmit gait cycle data wirelessly through smartphone Blynk application. The total cost to produce portable gait monitoring system is less than RM50. Despite its affordable price, it can produce reading and result that are on par with other wearable sensors device. The portable Smart Shoe is capable to detect the gait cycle of a healthy subject. The collected data demonstrate consistent gait pattern during normal walking condition. This data, tabulated in the table and graphs, indicates the subject's healthy status, as they are no significant change or irregularities in the data.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this paper.

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